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Methodology and applications of city level CO_2 emission accounts in China

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A B S T R A C T

China is the world's largest energy consumer and CO_2 emitter. Cities contribute 85% of the total CO_2 emissions in China and thus are considered as the key areas for implementing policies designed for climate change adaption and CO_2 emission mitigation. However, the emission inventory construction of Chinese cities has not been well researched, mainly owing to the lack of systematic statistics and poor data quality. Focusing on this research gap, we developed a set of methods for constructing CO_2 emissions inventories for Chinese cities based on energy balance table. The newly constructed emission inventory is compiled in terms of the definition provided by the IPCC territorial emission accounting approach and covers 47 socioeconomic sectors, 17 fossil fuels and 9 primary industry products, which is corresponding with the national and provincial inventory. In the study, we applied the methods to compile CO_2 emissions inventories for 24 common Chinese cities and examined uncertainties of the inventories. Understanding the emissions sources in Chinese cities is the basis for many climate policy and goal research in the future.

1. Introduction

Cities are the main consumers of energy and emitters of CO_2 throughout the world. The International Energy Agency (IEA) (2009) estimates that CO_2 emissions from energy use in cities will grow by 1.8% per year between 2006 and 2030, with the share of global CO_2 emissions rising from 71% to 76%. As a result of urbanization, the world's urban population grew from 220 million in 1900 (13% of the world's population) to 3530 million in 2011 (52% of the world's population) (Kennedy et al., 2015). Cities are major components in the implementation of climate change adaption and CO_2 emission mitigation policies. Understanding the emission status of cities is considered a fundamental step for proposing mitigation actions.

With rapid economic development, lifestyle change and consumption growth (Hubacek et al., 2011), China is now the world's largest consumer of primary energy and emitter of greenhouse gas emissions (Guan et al., 2009). According to U.S. Energy Information Administration (EIA) (2010) and British Petroleum (2011), China produces 25% of global CO_2 emissions, consumes 20% of global primary energy. Among CO_2 emission sources, 85% of China's emissions are contributed by energy usage in cities, which is much higher than that of the USA (80%) or Europe (69%) (Dhakal, 2009, 2010). An effective understanding of the energy consumption and emission status of common cities in China is urgently required to practice mitigate climate change.

There are some challenges for the compilation of greenhouse gas inventories at the city level for China. First, it is difficult to define a city's boundary for greenhouse gas emissions accounting because energy and material flows among cities may bring a large quantity of cross-boundary greenhouse gas emissions (Liang and

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Zhang, 2011; Wolman, 1965). Commercial activities are much more frequent among cities, compared with inter-provinces/nations, which leads to a great challenge. Second, data for energy consumption and industry products are incomparable and very limited for most cities in China (Liu et al., 2012b). Complete energy balance tables and energy inventories are available for Chinese megacities only (Beijing, Tianjin, Shanghai, and Chongqing), another 250 + cities of various sizes and development stages lack consistent and systematic energy statistics. Data used in previous studies are from various sources, including city statistical documents, remote sensing images, direct interviews with local governmental officials, and published reports and literature (Xi et al., 2011). Those data require systematic reviews for consistency and accuracy.

In this study, we develop a feasible methodology for constructing CO_2 emissions inventories for Chinese cities from fossil energy consumption and industrial processes, aiming at providing unified and comparable energy and emission statistics for generic Chinese cities. The emission inventories are calculated based on cities' energy balance tables, which are consistent with national and provincial emission accounts by previous studies (Liu, 2016; Liu et al., 2015). We verify the method by comparing our results with previous studies, as well as calculating the uncertainties of the estimates. We apply the method to 24 Chinese cities in this study, and identify the main contributors to the cities' CO_2 emissions.

2. Literature review of emission inventory at city level

The CO_2 emission inventory has captured both public and academic attention in recent years. Most of the previous emissions inventories were developed at the national level (Guan et al., 2008, 2012; Menyah and Wolde-Rufael, 2010; Mi et al., 2017; Peters et al., 2012), provincial level (Meng et al., 2011; Shan et al., 2016a; Yu et al., 2014), and sectoral level (Liu et al., 2012a; Shan et al., 2016b; Shao et al., 2011). Emission inventories for cities are limited (Brondfield et al., 2012; Chen and Chen, 2012; Dodman, 2009; Hasegawa et al., 2015; Hillman and Ramaswami, 2010; Hoornweg et al., 2011; Kennedy et al., 2011; Ramaswami et al., 2008).

Most city-level GHG emissions inventories were calculated using a bottom-up approach in the previous research, i.e., by using energy data from certain sector sets. The sectors set are different from study to study. Wang et al. (2012) calculated carbon emissions of 12 Chinese provincial capital cities by 6 sectors, including industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste. Differently, Kennedy et al. (2010) and their subsequent research (Kennedy et al., 2009, 2014) compiled carbon emissions inventories that cover electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, industrial processes and product use, and waste for 10 global megacities. Creutzig et al. (2015) built an energy/emission dataset including 274 cities, and present the aggregate potential for urban climate change mitigation.

Compared with global research, CO_2 emission inventory research on Chinese cities has not been well documented. Dhakal (2009) compiled emission inventories for 35 provincial capital cities in China. Liu et al. (2012b) complied the scope 1 and 2 emission inventories of four Chinese municipalities from 1995 to 2009. Scope 1 emissions include CO_2 induced from direct use of primary energy and industrial activity within territorial boundary. Scope 2 emissions refer to the out boundary purchased electricity related CO_2 emissions. Sugar et al. (2012) compiled the 2006 emission inventories of Chinese municipalities and compared the results with 10 other global mega cities.

Above all, the current emission inventories of Chinese cities are compiled by sectors, which are not consistent with each other, as well as the national/provincial inventories. The national/provincial inventories are usually compiled according to energy balance tables in China. What's more, most existing research has focused on a few specific megacities, such as four municipality cities (Beijing, Tianjin, Shanghai and Chongqing) and few provincial capital cities, which have consistent and systematic energy statistics. Accurate accounts of cities' CO_2 emissions are needed for further analysis on emission-economic nexus (Chen and Chen, 2017, 2016; Chen et al., 2015; Lu and Chen, 2016; Meng et al., 2017; Mi et al., 2016; Shao et al., 2016).

3. Methodology

3.1. Boundary and method for emissions accounting

In accordance with the guidelines from the Intergovernmental Panel on Climate Change (IPCC) regarding the allocation of GHG emissions, we consider the administrative territorial scope for each city's CO_2 emissions accounting in this study. Administrative territorial emissions refer to the emissions that occur within administered territories and offshore areas over which one region has jurisdiction (IPCC (2006)), including emissions produced by socioeconomic sectors and residence activities directly within the region boundary (Barrett et al., 2013). The CO_2 emissions inventory consists of two parts, emissions from fossil fuel consumption and from industrial processes. Detailed scope and boundary for emission accounting are shown in Table 1.

The notations and abbreviations used in the following emission calculation and data collection are gathered in Table 2.

3.2. Calculation of CO_2 emissions and inventory construction

First, we calculate the emissions from fossil fuel combustion. The emissions are calculated for 17 fossil fuels and 47 socioeconomic sectors. The 47 socioeconomic sectors are defined according to the Chinese National Administration for Quality Supervision and Inspection and Quarantine (NAQSIQ) (2011), which include all possible socioeconomic activities conducted in a Chinese city's administrative boundary (shown in SI Table S1). We include 17 fossil fuels in this paper that are widely used in the Chinese energy system (Department of Energy Statistics of National Bureau of Statistics of the People's Republic of China (NBS), 1986–2013), see Table 3.

We adopt the IPCC (2006) sectoral approach to calculate the CO_2 emissions, which is widely applied by research institutions and scholars (European Commission, 2014; Feng et al., 2013; Lei et al., 2011; Liu et al., 2014; United Nations Framework Convention on Climate Change (UNFCCC); Wiedmann et al., 2008; Zhou et al., 2010). The fossil fuel-related CO_2 emission equals to activity data (fossil fuel consumption) times emission factors, see Eq. (1).

$$CE_{energy} = \sum_i \sum_j CE_{ij} = \sum_t \sum_j AD_{ij} \times NCV_i \times EF_i \times O_{ij},\ i \in [1,17], j \in [1,47] \quad (1)$$

The subscript i and j in the equation refers to fossil fuel types and sector respectively, which are corresponding with those in Table 3 and SI Table S1. CE_{ij} represents the CO_2 emissions from fossil fuel i combusted in sector j ; AD_{ij} represents fossil fuel consumption. NCV_i (net caloric value), EF_i (emission factor), and O_{ij} (oxygenation efficiency) are emission parameters of different fossil fuels. The units of the three parameters are "$J/tonne\ fossil\ fuel\ consumption$", "$tonne\ CO_2/J$", and "%" respectively.

Both IPCC (2006) and NDRC (2011) provide default emission

Table 1
Scope definition for city CO_2 emission accounting.

Spatial boundaries	Components
In-boundary fossil fuel related CO_2 emissions	Primary-industry use (farming, forestry, animal husbandry, fishery and water conservancy) Industrial use (40 sub-sectors) Construction use Tertiary-industry use (2 sub-sectors) Residential use (Urban and Rural) Other
In-boundary process-related CO_2 emissions	CO_2 emissions from 9 industrial processes

Note: Due to the city's administrative boundary spanning both urban and rural geographies in China, the residential energy use are also consisted of 2 categories: urban and rural.

Table 2
Notations, abbreviations and their meaning used in this study.

Notations	Explanation
Subscript i	Fossil fuel type
Subscript j	Sector
Subscript t	Industrial process
CE_{ij}	CO_2 emissions from fossil fuel i combusted in sector j
CE_t	CO_2 emissions from industrial process t
AD_{ij}	Consumption of fossil fuel i in sector j
NCV_i	Net caloric value of fossil fuel i
EF_i	Emission factor of fossil fuel i
O_{ij}	Oxygenation efficiency of fossil fuel i combust in sector j
EF_t	Emission factor of industrial process t
EBT	City's energy balance table
$EBTp$	Provincial energy balance table
P	City-province percentage, which is calculated with industrial outputs and population, reflecting the percentage relation between a city and its province
ADS	Short for "Industrial enterprises above designated size"
m	ADS multiplier, refers to the multiple of the whole industrial output to that of the industry above the designated size
AD_i	Consumption of fossil fuel i of the whole industry
AD_{i-ADS}	Consumption of fossil fuel i at ADS scale
AD_{ij-ADS}	Consumption of fossil fuel i in sector j at ADS scale
AD^*_{j-ADS}	Comprehensive energy consumption of sector j at ADS scale
AD_t	Production of industrial process t

factors for fossil fuels. However, based on measurements of 602 coal samples from the 100 largest coal-mining areas in China (Liu et al., 2015), the emission factors recommended by the IPCC and NDRC are frequently higher than the real emissions factors. In this study, we adopted the newly measured emission factors, which we assume to be more accurate than the IPCC and NDRC default values (see Table 3). We considered different oxygenation efficiency for fossil fuels burnt in different sectors, as the combustion technology level of sectors are different in China.

Energy used as chemical raw material and loss during transportation are removed from the total energy consumption to avoid double counting. Emissions from electricity and heat generated within the city boundary are counted based on the primary energy input usage, such as raw coal (Peters et al., 2006). Our administrative territorial emission inventory excludes emissions from imported electricity and heat consumption from outside the city boundary, as well as the inter-city transportation energy consumption. We only focus on fossil fuel consumed within the city boundary.

In the second part, we calculate CO_2 emissions from 9 industrial processes (see Table 4). The 9 industrial processes are emission-intensive processes, contributing over 95% of the total process-related emissions in China (Shan et al., 2016b). The process-related emissions are CO_2 emitted as a result of chemical reactions in the production process, not as a result of the energy used by industry. Emissions from industrial processes are factored into the corresponding industrial sectors in the final emissions inventory. We estimate the process CO_2 emissions in Eq. (2).

$$CE_{process} = \sum_t CE_t = \sum_t AD_t \times EF_t, \quad t \in [1, 9] \tag{2}$$

The subscript t in the equation refers to industrial processes, which are corresponding with those in Table 4. CE_t and EF_t represent the CO_2 emissions and emission factor for industrial process t. Most of the emission factors are collected from IPCC (2006), except that of cement production, which is collected from our previous study on China's cement process (Liu et al., 2015), shown in Table 4.

By including the emissions from fossil fuel consumption and industrial processes, the emissions inventory designed in this paper includes all administrative boundary territorial CO_2 emissions from 47 sectors, 17 energy types and 9 main industrial processes.

3.3. Activity data requirement and process

Fig. 1 shows the overall methodology framework designed for the construction of emissions inventories for Chinese cities in this study. We need the energy balance table (EBT), industrial sectoral fossil fuel consumption (AD_{ij}), and industrial products' production (AD_t) to calculate the CO_2 emissions from both fossil fuel combustion and industrial processes. Generally, the data for cities can be collected from city's municipal bureau of statistics, such as Hefei Municipal Bureau of Statistics (2011) and Xiamen Municipal Bureau of Statistics (2011).

3.3.1. Energy balance table

The Energy Balance Table (EBT) is an aggregate summary of energy production, transformation and final consumption in one area (Qiu, 1995), which could reveal the energy flow of one region. The sectoral consumption of fossil fuels from EBT can be used as activity data to calculate the fossil fuel-related CO_2 emissions. Detailed illustration of EBT are shown in the Support Information. However, due to the poor data quality of Chinese cities, some cities don't compile EBT in their statistical yearbook. The following three cases cover all the possible EBT availabilities of Chinese cities.

3.3.1.1. Case α: city with energy balance table. Some cities compile EBT in their statistical yearbooks, such as Guangzhou (Guangzhou Municipal Bureau of Statistics, 2011). We collect the fossil fuel consumption from the table directly for emission estimation.

3.3.1.2. Case β: city without energy balance table. For cities such as Hefei and Xiamen, there is no EBT in their statistical yearbooks (Hefei Municipal Bureau of Statistics, 2011; Xiamen Municipal Bureau of Statistics, 2011). In these cases, we deduce the city's EBT from its corresponding provincial energy balance table ($EBTp$). First, we define a city-province percentage P in Eq. (3), which can be calculated using different indexes, such as industrial outputs and population. The equation reflects the percentage relation between a city and its province.

$$P = Index_{city} / Index_{province} \times 100\% \tag{3}$$

With the city-province percentage, P, we scale down the provincial energy balance table to the city level (see Eq. (4)). For 'Input & Output of Transformation' and 'Loss' part of EBT, we use the industrial output as index to calculate the city-province percentage P,

Table 3
Emissions parameters of fossil fuel combustion.

No. (i)	Energy types	$NCV_i(PJ/10^4$ $tonnes, 10^8$ m$^3)$	$EF_i(tonneCO_2/TJ)$
1	Raw coal	0.21	96.51
2	Cleaned coal	0.26	96.51
3	Other washed coal	0.15	96.51
4	Briquettes	0.18	96.51
5	Coke	0.28	115.07
6	Coke oven gas	1.61	78.8
7	Other gas	0.83	78.8
8	Other coking products	0.28	100.64
9	Crude oil	0.43	73.63
10	Gasoline	0.44	69.3
11	Kerosene	0.44	71.87
12	Diesel oil	0.43	74.07
13	Fuel oil	0.43	77.37
14	Liquefied petroleum gas	0.51	63.07
15	Refinery gas	0.47	73.33
16	Other petroleum products	0.43	74.07
17	Natural gas	3.89	56.17

because energy transformation departments belong to industry. For 'Final consumption' in *EBT*, we use the corresponding outputs of each sector as the indexes. For 'Residential consumption', we use population as the index. The industrial output and population can be collected from each city's statistical yearbook as well.

$$EBT = EBTp \times P \tag{4}$$

3.3.1.3. Case γ: city without energy balance table, but with table of "transformation usage of energy types". Some cities do not have a *EBT* in their statistical yearbooks, but have compiled a table of "Transformation usage of energy types", such as Huangshi (Huangshi Municipal Bureau of Statistics, 2011) in Hubei province. The transformation table presents the energy input and output during transformation process, and can be used to make our deduced *EBT* more accurate. We modify the "Input & Output of Transformation" section of the deduced city *EBT* with the table of transformation.

3.3.2. Industry sectoral energy consumption

The *EBT* counts industry as one entire component of all consumption components. However, industry is the major energy consumption component and contributes the majority of greenhouse gas emissions. In addition, industry is also the primary area for applying low carbon technologies (Liu et al., 2013). Based on the industry sectoral energy consumption, we could expend the final energy consumption of industry in *EBT* into 40 sub-sectors with corresponding to the industry classification provided by NAQSIQ (Xu, 2005). The extended energy balance table consists of 47 final consumption sectors and can provide a more detailed illustration of energy utilization for both industry and the entire city. Following the methods below, we could deduce the industry sectoral energy consumption of Chinese cities with different data qualities.

3.3.2.1. Case A: city with industry sectoral energy consumption by types (AD_{ij}). For some cities, the sectoral energy consumption by types of the whole industry is provided in the statistical yearbook. We use the data directly.

3.3.2.2. Case B: city with sectoral energy consumption by types of industry enterprises above designated size (AD_{ij-ADS}) and energy consumption by types of the whole industry (AD_i). For cities such as Guangzhou, the industrial statistics is carried on above designated size (ADS) scale, which means the statistical data in its yearbook only includes industry above designated size (Guangzhou Municipal Bureau of Statistics, 2011). The enterprise above designated size refers to the enterprise with annual main business turnover above 5 million Yuan. Guangzhou has sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) and energy consumption by types of the whole industry (AD_i) in its yearbook. In this case, we expand AD_{ij-ADS} by AD_i to obtain AD_{ij} in Eq. (5).

$$AD_{ij} = AD_{ij-ADS} \Big/ AD_{ij-ADS} \times AD_i, \; i \in [1, 17], \; j \in [2, 41] \tag{5}$$

3.3.2.3. Case C: city with sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) only. These cities are the most common types in terms of data collection for Chinese cities. They only have sectoral energy consumption by types of ADS industry (AD_{ij-ADS}) in their statistical yearbooks. Most cities are classified into this case; these include Hefei and Xiamen (Hefei Municipal Bureau of Statistics, 2011; Xiamen Municipal Bureau of Statistics, 2011). To calculate the sectoral energy consumption of the whole industry (AD_{ij}), we expand AD_{ij-ADS} to AD_{ij} by the ADS multiplier m (see Eq. (6)).

$$\begin{aligned} AD_{ij} &= AD_{ij-ADS} \times m \\ &= AD_{ij-ADS} \times O_{industry} \Big/ O_{ADS}, \; i \in [1, 17], \; j \in [2, 41] \end{aligned} \tag{6}$$

$O_{industry}/O_{ADS}$, which is the ADS multiplier (m) in this paper, refers to the multiple of industrial output to that of the industry above the designated size.

3.3.2.4. Case D: city with total energy consumption by types of ADS industry (AD_{i-ADS}) only. For cities such as Weifang and Huangshi, we can collect only the total energy consumption by types of ADS industry (AD_{i-ADS}) from the statistical yearbooks (Huangshi Municipal Bureau of Statistics, 2011; Weifang Municipal Bureau of Statistics, 2011). In this case, we first scale up AD_{i-ADS} to AD_i by the ADS multiplier m and then divide AD_i into each sector by the sectoral comprehensive energy consumption of the ADS industry (AD^*_{j-ADS}) (refer to Eq. (7)). If one city does not have AD^*_{j-ADS}, we use the sectoral industry output instead.

$$AD_{ij} = AD_{i-ADS} \times m \times AD^*_{j-ADS} \Big/ \sum_j AD^*_{j-ADS}, \; i \in [1, 17], \; j \in [2, 41] \tag{7}$$

AD^*_{j-ADS} in the equation refers to the comprehensive energy consumption of sector j at ADS scale. AD_{i-ADS}, as explained above, refers to the total energy consumption of fossil fuel i at ADS scale.

With these three cases, we collect and deduce the industry sectoral energy consumption by types for one city. By replacing the final energy consumption of industry in the *EBT* with the sub-sectoral detail, we obtain the extended energy balance table.

3.3.3. Industrial products' production

Data collection for the production of industrial products is much easier and universal. Every city has the "Production of industrial products" table in its statistical yearbook. A portion of the production is derived from industrial enterprises above the designated size. If we expand the production above the designated size (AD_{t-ADS}) by the city's ASD multiplier m defined above, we can obtain the total production of each industrial product (AD_t), shown in Eq. (8), in which the subscript $t \in [1, 9]$ represents the different industrial products (refer to Table 4).

Table 4
CO_2 emission factors for 9 main industrial processes.

No.(t)	Industrial Processes	EF_t(tonne CO_2/tonne)
1	Ammonia production	1.5000
2	Soda Ash production	0.4150
3	Cement production	0.2906
4	Lime production	0.6830
5	Ferrochromium production	1.3000
6	Silicon metal production	4.3000
7	Ferro-unclassified production	4.0000
8	Ferrous Metals production (Coke usage as reducing agent)	3.1000
9	Nonferrous Metals production (Coke usage as reducing agent)	3.1000

$$AD_t = AD_{t-ADS} \times m,\ t \in [1,9] \tag{8}$$

3.4. Validation

In order to verify our method, we apply this method to 5 cities firstly and compare the fossil fuel related CO_2 emissions with previous research. The fossil fuel contributes more than 90% of the total CO_2 emissions. Therefore, the comparison of fossil fuel related CO_2 emissions with other research can be a validation of our estimates. In the China High Resolution Emission Gridded Data (CHRED) with 1 km resolution built by Chinese academy for environmental planning (CAEP), they estimated few cities' fossil fuel-related CO_2 emissions based on energy consumption data collected in a bottom-up way based on industrial facility data and other information (Cai, 2011, 2012; Cai and Zhang, 2014; Wang et al., 2014). The 5 cities, Hefei, Xiamen, Weifang, Huangshi, and Guangzhou, contain all the different cases we deduce the city's data, see Table 5.

From Table 5 we can see that the difference of CO_2 emissions between our study and CAEP's research is within 10%. According to previous research, emissions from OECD countries may have an uncertainty of 5%–10%, while the uncertainty for non-CECD countries may be 10%–20% (Marland, 2008; Olivier and Peters, 2002). Therefore, we believe our estimations are relatively accurate and our method is effective and reliable.

4. Inventory construction and uncertainty of 24 cities

In this paper, we apply our method to 24 cities and compile the CO_2 emissions inventory for 2010. These 24 cities, which cover all the possible situations for data collection cases discussed above (see SI Table S3), are in different sociometric developmental stages. Per capita GDP of the 24 cities varies from 14.80 thousand Chinese Yuan (Zunyi) to 106.88 thousand (Shenzhen). 9 of the 24 case cities are provincial capital cities, which are larger and more affluent than the other 15 non-capital cities generally. Fig. 2 shows the locations and total CO_2 emissions of these 24 case cities.

Table 6 shows socioeconomic indexes of the 24 case cities. All necessary activity data were collected from each city's statistical yearbook. Detailed data source of this study is shown in the Support Information. We present the data collection and calculation results in SI section 3 and 4, Tables S3–S6. We have included all data used and our results online at our database: http://www.ceads.net (free to download after registration).

4.1. Results

In 2010, total CO_2 emissions of the 24 cities varied widely from 4.86 to 104.33 million tonnes. Tangshan and Guangzhou belong to the highest emission class, with more than 100 million tonnes, followed by Handan, Hohhot, and Weifang, Shenyang, Xi'an, and Changsha which have between 50 and 100 million tonnes. All these eight cities have heavy-intensity industries, such as coal mining and manufacturing. The third emission class includes all cities with CO_2 emissions between 25 and 50 million tonnes, i.e., Jixi, Shenzhen, Nanchang, Hefei, Chengdu, Huangshi, and Zunyi. The remaining cities belong to the lowest emissions class; these include cities with less heavy-intensity manufacturing industry/more developed service industry (i.e., Yichang, Nanning, Xiamen, and Suqian) and cities located in more remote areas with a smaller population and smaller GDP (i.e., Dandong, Nanping, Baicheng, Zhoushan, and Wuwei) compared with the other three classes.

If we divide the total CO_2 emissions by the population, we obtain the CO_2 emissions per capita of the 24 case cities (shown in Table 6). We find that, among the 24 case cities, the CO_2 emissions per capita in Hohhot is the highest, with 29.67 tonnes, followed by Jixi (22.84 tonnes), Shenzhen (14.69 tonnes), and Tangshan (14.20 tonnes). The four cities with the lowest CO_2 emissions per capita are Suqian (1.18) Nanping (2.38), Chengdu (2.53 tonnes), and Wuwei (2.54). In the same way as the total CO_2 emission distribution, cites with coal mines and heavy-intensity industry have high CO_2 emissions as well as high CO_2 emissions per capita, such as Jixi, Hohhot and Tangshan. Cities located in remote areas and in less developed stages have lower CO_2 emissions per capita as well as less CO_2 emission.

4.2. Uncertainty analysis

Analysing uncertainty is an important tool for improving emission inventories that contain uncertainty (Jonas et al., 2014; Shen et al., 2014). Different methods are used to analyse the uncertainty of emissions, Jonas et al. (2010) describe four relevant uncertainty terms and six techniques that can be used to analyse uncertain emission changes. In this study, we employ Monte Carlo simulations to calculate the uncertainties of 20 Chinese cities' CO_2 emissions, which is recommended by IPCC (Intergovernmental Panel on Climate Change (IPCC), 2006) and widely used in previous research (Lang et al., 2014).

As the CO_2 emission is calculated as product of activity data and emission factors, therefore uncertainty comes from two parts: activity data (fossil fuel consumption) and emission factors. According to Monte Carlo analysis, we should assume individual probability density functions for the two variables firstly, then simulate the CO_2 emissions values with the assumed functions for many times (Penman, 2000). Industrial processes emit much less CO_2 (9.89% of the total CO_2 emissions) compared with fossil fuel combustion. What's more, emissions from industrial process are generally with less uncertainties (Liu et al., 2015; Zhao et al., 2011). Therefore, we only consider uncertainty from fossil fuel consumption in this study. We calculate the uncertainty of both the overall CO_2 emissions and sub-sectors' emissions of the 24 city cases in this study.

We assume normal distributions for both activity data and emission factors (Liu et al., 2015; Zhao et al., 2011). The coefficients of variation (CV, the standard deviation divided by the mean) of different emission factors and fossil fuel consumptions are chosen from previous literature, see Table 7. We repeat the simulation procedure for 20,000 times in Monte Carlo analysis. Table 8 shows the total uncertainties of 24 cities' emissions in 2010 with 95% Confidence Interval.

The average uncertainty of total CO_2 emissions of the 24 case cites is from −4% to 4%, falling in the range of 10%–20% for non-OECD countries (Marland, 2008; Olivier and Peters, 2002). This

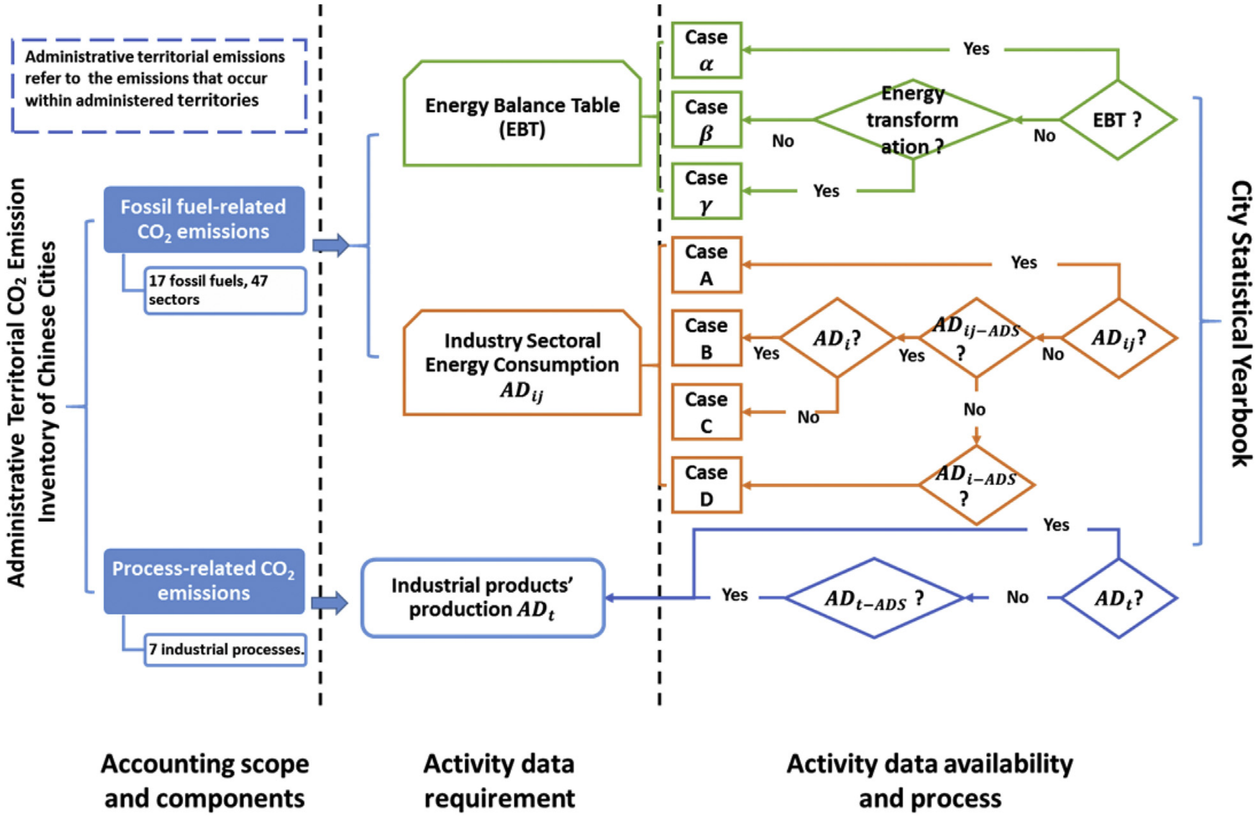

Fig. 1. *CO_2 emissions inventory construction framework for Chinese cities*. The subscript "ADS" is short for "above designated size". AD_{ij-ADS}/AD_{i-ADS} refers to sectoral/total consumption of fossil fuel *i* in industry above designated size (see section "3.3.2 Industry sectoral energy consumption" for more details).

illustrates that our estimations are relatively accurate and realisable. Among the 24 cities, CO_2 emissions of Shenzhen have the smallest uncertainty (−2%, 2%), while emissions of Jixi have the highest uncertainty (−6%, 6%). As the largest contributor of CO_2 emissions (39.19% of the total emissions averagely of the 24 cities in this study), the emissions from electricity generation sector has the largest uncertain averagely (−6%, 6%) among different sectors. This is caused by large amount of coal combusted in coal-fired power plant, uncertainty of coal's emission factor is the highest among energy types, despite the fossil fuel consumption in electricity generation sector has a low uncertainty. In contrast to power plant, CO_2 emission from service sector (transportation and territorial industries) have the lowest uncertainty averagely (−2%, 2%). Much oil and gas are used in these sectors compared with power plant, which have lower uncertainties of emission factor. Detailed uncertainties by sectors are shown in SI Table S6.

5. Discussion

5.1. Emissions of different fossil fuel types and industrial process

Fig. 3 shows the energy type distribution for the CO_2 emissions inventory in 2010. Raw coal is the largest primary source of emissions among the 17 fossil fuel types, with an average percentage of 58.2%. The high CO_2 emissions are induced by the large consumption and high carbon content of raw coal (Pan et al., 2013). Coal is the largest primary energy source in China. About 70% of the total energy used in China comes from coal in 2010 (NBS (2016)).

For example, Jixi is one of the coal bases in China and produced 20.46 million tonnes raw coal in 2010. Coal and its related products (cleaned coal, other washed coal, briquettes, and coke) become the primary energy types in Jixi. In 2010, 42.28 million tonnes of CO_2 emissions were produced by coal and combustion of coal products; this is of 97.84% of Jixi's total emissions. Similar to Jixi, Inner Mongolia province is also a main coal base in China. As the provincial capital city of Inner Mongolia, Hohhot uses coal and coal products as the main energy types as well. In 2010, Hohhot produced 6.01 million tonnes raw coal, 0.60 million tonnes coke, and generated 35.26 billion watt-hour electricity in fire power plant in 2010. Coal and coal-related products contributed 57.57 million tonnes of CO_2 emissions (84.34%) to Hohhot's total CO_2 emissions.

In addition to coal, diesel oil is another important source of CO_2 emissions, with an average percentage of 8.31%. Diesel oil is widely used most types of transportation, such as oversize vehicle and ship. Among the 24 cities, Shenzhen, Zhoushan, Guangzhou, and Xiamen have a much higher percentage of diesel use (32.34%, 22.64%, 14.79%, and 13.57% respectively) than the average percentage Diesel oil is widely used by truck and cargo shippers. These four cities are located in the south and on the southeast coast of China; they are important ports. The freight and transportation industry is more developed in these cities than others. Take Shenzhen as an example, there are 172 berths in Shenzhen harbour with 79 berths over 10 thousand tonnes class, the cargo handled at seaports are 220.98 million tonnes in 2010. The waterways and highway freight traffic in 2010 are 198.47 and 58.59 million tonnes, taking a percentage of 1.38% and 0.70% over the whole Chinese 300 + cities. Therefore, the diesel oil and Transportation sectors has a higher percentage of these cities' total CO_2 emissions compared with other cities (also see Sect. 5.2).

Industrial processes also contribute much to a city's total CO_2 emissions. The total CO_2 emissions produced during the industrial process of the 24 case cities are 92.10 million tonnes, which is 9.89%

Table 5
Validation of fossil fuel-related CO_2 emission estimations.

	Our estimation	CAEP	Difference between two results	Case type
Hefei	30.22	33.23	-9%	β, C
Xiamen	11.82	12.67	-7%	β, C
Weifang	60.17	57.18	5%	α, D
Huangshi	19.53	20.61	-5%	γ, D
Guangzhou	96.13	96.67	-1%	γ, B

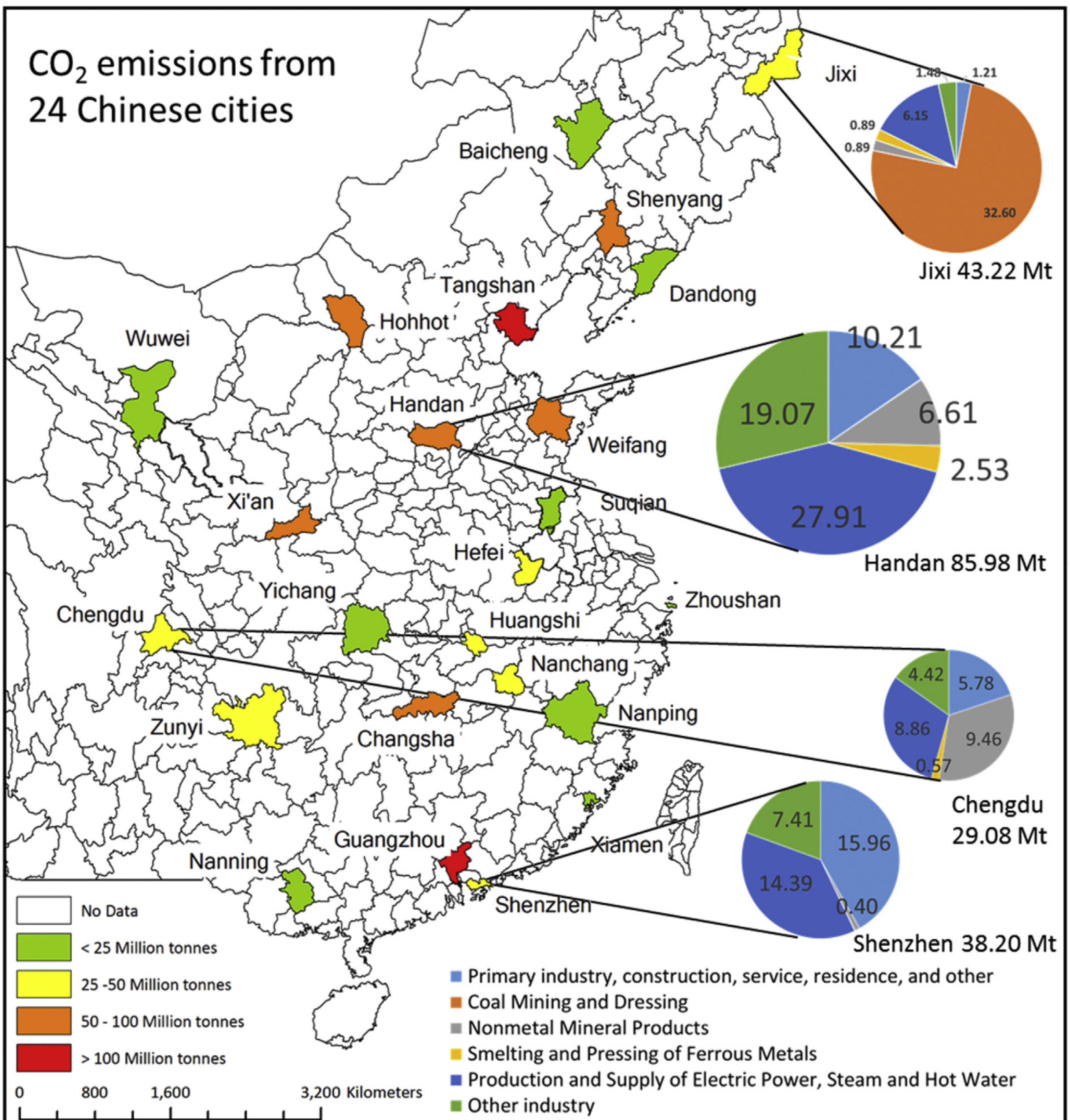

Fig. 2. CO_2 emissions of the 24 case cities, 2010, million tonnes.

Table 6
Socioeconomic-emission indexes of 24 cities.

City	Location	Per capita GDP (10^6 Yuan)	CO_2 emission (Mt)	Per capita emissions (t)	CO_2 intensity (t/10^3 Yuan)
Hefei	Provincial capital, Central east	54,796	32.49	6.56	0.12
Nanping	Southeast	26,279	7.49	2.38	0.10
Xiamen	Southeast	58,337	11.82	6.57	0.06
Wuwei	Northwest	10,621	4.86	2.54	0.21
Guangzhou	Provincial capital, South	103,625	100.50	12.47	0.09
Shenzhen	South	106,880	38.20	14.69	0.04
Nanning	Provincial capital, Southwest	25,622	23.30	3.30	0.13
Zunyi	Southwest	14,799	26.53	3.38	0.29
Handan	Central north	26,143	85.98	8.92	0.36
Tangshan	Central north	59,389	104.33	14.20	0.23
Jixi	Northeast	22,083	43.22	22.84	1.03
Huangshi	Central	28,427	26.75	10.28	0.39
Yichang	Central	38,181	25.00	6.26	0.16
Changsha	Provincial capital, Central	66,443	52.89	8.11	0.12
Baicheng	Northeast	21,973	7.41	3.65	0.17
Suqian	Central east	22,525	6.45	1.18	0.06
Nanchang	Central	43,769	36.62	7.29	0.17
Dandong	Northeast	29,893	9.07	3.76	0.12
Shenyang	Northeast	62,357	62.82	8.73	0.13
Hohhot	Provincial capital, North	66,929	68.25	29.67	0.37
Weifang	Central east	34,273	66.37	7.59	0.21
Xi'an	Provincial capital, Central west	38,341	55.76	7.12	0.17
Chengdu	Provincial capital, Southwest	48,510	29.08	2.53	0.05
Zhoushan	Central east	66,581	6.13	6.32	0.10

of the total CO_2 emissions. For example, there are many manufacturing industries in Tangshan, particularly ‘non-metal mineral products’ and ‘smelting and pressing of ferrous metals’. The production of cement, iron, and steel in 2010 are 37.32 Mt, 65.67 Mt and 68.32 million m^3. Therefore, the industrial process contributes greatly to Tangshan's total CO_2 emissions. The CO_2 emissions from Tangshan's industrial process in 2010 were 18.80 million tonnes (18.01%), which is much higher than the average level. Changsha (10.32 tonnes), Yichang (9.87 tonnes), and Huangshi (7.22 tonnes) are similar manufacturing cities.

5.2. Emissions of different sectors

We summarise the CO_2 emissions of 47 socioeconomic sectors

Table 7
Coefficient of variance (CV) of different emission factors and fossil fuel consumptions.

CV of emission factor (Liu et al., 2015)		CV of fossil fuel consumption (Zhao et al., 2011)	
		Electricity generation sector	5% (Wu et al., 2010; Zhao et al., 2008)
Coal-related fossil fuel	3%	Other industries, construction	10% (Zhang et al., 2007)
Oil-related fossil fuel	1%	Residential fossil fuel use	20% (IPCC (2006))
Gas-related fossil fuel	2%	Transportation sector	16% (Karvosenoja et al., 2008)
		Primary industry	30% (Wang and Zhang, 2008)

Table 8
Uncertainties of 24 Chinese cities' CO_2 emissions in 2010 (million tonnes).

City	Uncertainty	City	Uncertainty
Hefei	30.22 (−4%, 4%)	Yichang	15.12 (−4%, 4%)
Nanping	5.92 (−4%, 4%)	Changsha	42.57 (−3%, 3%)
Xiamen	11.82 (−4%, 4%)	Baicheng	7.41 (−5%, 5%)
Wuwei	4.36 (−5%, 5%)	Suqian	5.00 (−3%, 3%)
Guangzhou	96.13 (−3%, 3%)	Nanchang	35.03 (−5%, 5%)
Shenzhen	38.20 (−2%, 2%)	Dandong	8.32 (−4%, 4%)
Nanning	17.06 (−4%, 4%)	Shenyang	61.01 (−4%, 3%)
Zunyi	22.53 (−5%, 5%)	Hohhot	65.12 (−5%, 5%)
Handan	81.91 (−4%, 4%)	Weifang	60.17 (−4%, 4%)
Tangshan	85.54 (−5%, 5%)	Xi'an	54.42 (−4%, 4%)
Jixi	42.85 (−6%, 6%)	Chengdu	23.13 (−3%, 3%)
Huangshi	19.53 (−4%, 4%)	Zhoushan	6.13 (−4%, 3%)

Note: The percentages in the parentheses indicate the 95% Confidence Interval around the central estimate.

into 9 key sectors in Fig. 3 in order to present sectoral contribution clearly. We also present four typical cities' sector share in Fig. 2. Industry sectors are the primary resources that contribute to a city's CO_2 emissions. Approximately 80.80% of the total CO_2 emissions are contributed by industry sectors, on average. Among the 40 sub-industry sectors defined in this paper, the “Electricity generation” sector produces the most CO_2 emissions, generating 39.19% of the total CO_2 emissions, on average. This generation is caused by the huge quantities of electricity generated in coal-fired power plants.

The “non-metal mineral products” sector contributes a lot of CO_2 emissions to the total emissions as well, taking a percentage of 12.80% averagely. This sector includes all the CO_2 emissions during non-metal mineral production, such as cement and lime. Tangshan (20.41 Mt), Changsha (14.98 Mt), Nanning (9.63 Mt), Huangshi (9.52 Mt), and Chengdu (9.46 Mt) have high CO_2 emissions in the “non-metal mineral products” sector compared with other cities. As discussed above, the cement production of Tangshan in 2010 is 37.32 Mt. Changsha (20.70 Mt), Nanning (11.87 Mt), Huangshi (14.49 Mt), and Chengdu (10.39 Mt) also produced more cement in 2010.

“Coal Mining and Dressing” sector is the third largest industrial source of CO_2 emissions (7.67% averagely), especially for Jixi (75.43%). This finding is because Jixi is a major coal-producing area in China, as discussed above. Large quantities of fossil fuels are consumed in mines to produce and wash coal and produce coke.

In addition, there are many “Smelting and pressing of ferrous Metals” industries in Tangshan and Handan. Tangshan produced 65.67 Mt iron and 68.32 million m^3 steel, while Handan produced 33.22 Mt iron and 36.84 Mt steel in 2010. The large production brings the two cities large CO_2 emissions of these sector (26.64 Mt and 8.10 Mt respectively).

In addition to industry sectors, service sectors also greatly contribute to total CO_2 emissions. The “service sectors” in Fig. 3 includes two components: “transportation” and “wholesale services”. CO_2 emissions from these two sectors generate an average of 12.23% of the emissions in the 24 cities. For Shenzhen, Guangzhou, Zhoushan, Xiamen, and Changsha, the CO_2 emissions that the service sectors contribute (33.16%, 28.39%, 25.11%, 19.18%, and18.39% respectively) are much higher than the average level. Among these five cities, Shenzhen, Guangzhou, and Zhoushan are located on the south/southeast coast of China. These cities are very important ports with high waterways and highway freight traffic, as discussed above. Xi'an and Changsha are inland transport junctions. The overall freight traffic of Xi'an and Changsha in 2010 are 343.23 and 229.47 Mt. The “transportation services” sectors of these five cities are well developed. In addition, Shenzhen has a larger share of tertiary industries. The proportion of value added by Shenzhen's

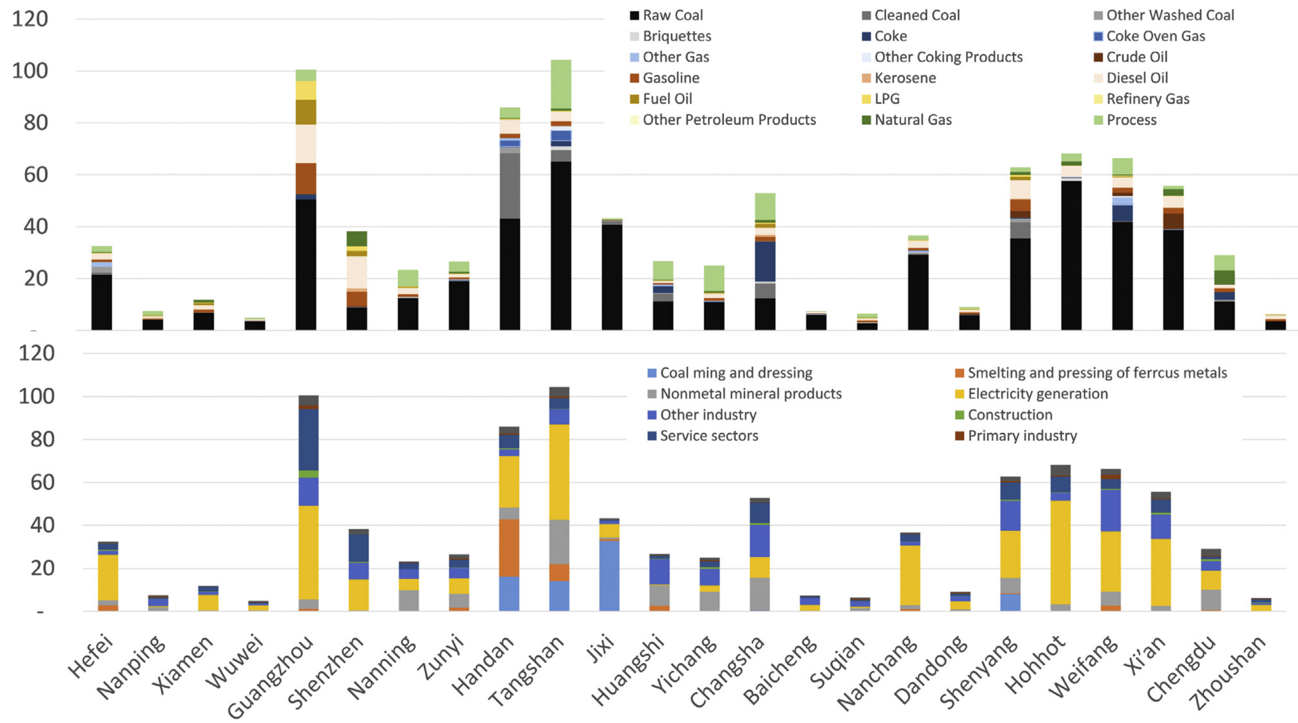

Fig. 3. CO_2 emissions by energy types and sectors (million tonnes, 2010).

tertiary industry is 52.7%, which is much higher than the national average of 44.2%. Therefore, the CO_2 emissions of Shenzhen's service departments are higher than those of other cities. The well-developed tertiary industry makes Shenzhen more affluent than other cities, the rural population of Shenzhen is 0 and per capita GDP is 106,880 Yuan in 2010, much higher than the national average level of 41,908 Yuan.

Primary industry and residential energy usage generate a small percentage of cities' CO_2 emissions in China. Based on the 20 case cities, the average percentage of the total CO_2 emissions generated by the two departments is 1.19% (primary industry) and 4.61% (residential energy usage).

5.3. Policy recommendation for emission reduction

As discussed above, coal and heavy emission intensity manufacturing industries are the primary emission sources within one city. Therefore, in order to reduce the CO_2 emissions in Chinese cities, we could take policy from two aspects. The first path is reducing the coal share in the energy mix and develop clean coal utilization strategy. The second one is reforming the industrial structure.

Reducing the coal share in the energy mix could decrease the emission intensity of one city. This is an effective way to reduce the CO_2 emissions while keep economic growing continually. Coal combustion emits more CO_2 to produce the same unit of heat compared with other energy types. Replacing coal by clearer energy types, such as nature gas, will help emission control in both Chinese cities and the whole world. In the 12th five-year plan (2011–2015) on energy, the central government proposed to control the total energy consumption and reduce coal share for the first time (NDRC, 2013). Efforts has been taken according to the government document these years and achieved initial success. The coal share in the energy mix decreased from 72.40% to 64.04% in the recent 10 years from 2005 to 2014, while the natural gas share doubled from 2.40% to 5.63%. According to the most up to data research at COP 21, the global carbon emissions decreased slightly by 2015 due to Chinese coal consumption decreasing, and renewable energy increasing globally (Le Quéré et al., 2015). Efforts should be planned and undertaken at the city level in the future. For example, we should replace coal gas with natural gas for residential use; cities with geography advantages should develop the renewable energy types, such as wind power, hydroelectricity and nuclear power. Beijing, as the capital city, has a more balanced energy mix compared with other cities. The coal and natural gas share in the energy mix is 20.41% and 21.13%, respectively, in 2014. Beijing has reduced 43% of its coal consumption (12.48 million tonnes) during 2007–2014, which is required by the "Air Pollution Prevention and Control Action Plan" (Ministry of Environmental Protection (P.R.China), 2013). Meanwhile, the consumption of natural gas increased by 144% (6.70 billion m^3). Benefit from this policy, Beijing's CO_2 emissions has remained stable since 2007 and has seen a slight decrease in recent years (Guan et al., 2016).

The other way to control CO_2 emissions in Chinese cities is reforming the industrial structure. Firstly, we should close all the non-permission coal mining and consuming enterprises, in which the kilns are usually backward and produced a lot of CO_2 emissions with low economic outputs. All the private and unregulated energy enterprises should be integrated into the corporations with the most developed and clean energy technologies. Secondly, the city government should also replace heavy emission intensity manufacturing industries with services sectors. Reviewing the emission intensity of the 24 case cities (see Table 6), we could find that cities with more heavy manufacturing industries usually have a higher emission intensity, such as Jixi, Huangshi, Hohhot, Zunyi and Tangshan. On the contrary, cities with more service sector activities have a smaller emission intensity, such as Shenzhen, Chengdu, Xiamen and Guangzhou. Through reforming the industrial structure, Chinese cities may not reduce CO_2 emissions at the expense of economic development, and achieve both environmental and social objectives.

6. Conclusion

This paper develops a feasible methodology for constructing territorial CO_2 emissions inventories for Chinese cities. By applying this methodology to cities, researchers can calculate the CO_2 emissions of any Chinese cities. This knowledge will be helpful for understanding energy utilization and identify key emission contributors and drivers given different socioeconomic settings and industrialisation phrase for different cities. Accurate accounts of cities' CO_2 emissions are considered a fundamental step for further analysis on emission-economic nexus, as well as proposing mitigation actions.

We applied this methodology to 24 cities and compiled the 2010 CO_2 emissions inventories for the cities. The results show that, in 2010, the "Production and supply of electric power, steam and hot water", "Non-metal mineral products", and "Coal mining and dressing" sectors produced the most CO_2 emissions. Additionally, coal and its products are the primary energy source in Chinese cities, with an average of 69.98%. In order to reduce the CO_2 emissions in Chinese cities, we could take policy to reduce the coal share in the energy mix and replace heavy emission intensity manufacturing industries with service sector with smaller emission intensity.

The study still contains some limitations. For example, we scale down the provincial energy balance table by using a city-province percentage. By using the different city-province percentages, the deduced table for the city may not be balanced. However, this is restrained by the data at city level. The method developed in this study is based on the most comprehensive data we can ever find. Further research will be conducted to improve the accuracy of city's emission data.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.075.

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